Adaptive strategies and goal management in car drivers

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Chapter 3

Performance of a complex dynamic task

Car driving is an example of a complex dynamic task, and this chapter will discuss the complexities that face the operator in such tasks. First, the next section (3.1) will give a normative task analysis: what do operators need to do. Section 3.2 will discuss some psychological aspects in performing complex tasks, and possible cognitive processes involved will be outlined. Although car driving is a complex task for the novice driver, most drivers can converse, tune the radio and perform other activities while driving. As experience grows, task behaviour becomes more automated, reducing the demands on drivers' working memory. In order to understand driving behaviour, it is thus necessary to know how behaviour in complex tasks becomes more efficient with experience. Sections 3.3 and 3.4 will therefore discuss how automaticity develops, and how explicit problem solving will become replaced by more automatic cue-response sequences as experience grows.

3.1 Demands on the operator: a normative task analysis

Complex dynamic tasks, such as air-traffic control, industrial process operation, and medical emergency handling, are characterised by a number of features (Bainbridge, 1997). First, these tasks are difficult to perform: they are complex and need co-ordination, organisation and planning of subtasks. Furthermore, they are performed in dynamic environments where circumstances can change immediately and without warning. Operators therefore need flexibility to adapt their behaviour to new information and situations. At the same time, they need to keep their behaviour goal-directed and resist distraction. They also need a good mental overview of the task situation to be able make reliable predictions about the future.

Organisation and planning

Complex dynamic tasks often involve performing several subtasks, or involve controlling several different variables (Bainbridge, 1997). Because of this multitasking, and because one subtask may not be finished before another is started, subtasks have to be interleaved. This makes it necessary that subtasks are organised and planned. Subtasks and variables can be dependent on each other: There can be a strict order in which subtasks have to be performed; subtasks can be hierarchically organised. When subtask hierarchies are large, or the number of subtasks is large, this implies heavy use of working memory.

It may not be possible to perform all subtasks simultaneously. Operators therefore have to switch between the different (sub)tasks on the basis of their priority. Usually, not all subtasks are equally important for achieving the main task goal, and it is often possible to postpone or even give up a subtask. High-priority situations taxes working memory heavily, as operators have to remember which subtask they were performing before the emergency occurred. After dealing with the emergency, they furthermore have to determine whether it is still opportune to finish it.

Dynamic environment

The tasks or variables that have to be controlled are not static, but may change even if the operator does not take any action. To prevent errors, operators have to take anticipatory actions: rather than waiting for an emergency situation to develop, operators have to prevent it from occurring. Actions therefore not only have to be correct and of the right size, but they also have to be timed correctly.

Still, events can happen that are unexpected. This can happen either because elements in the environment itself are unpredictable, or because the task itself is so complex that it is not possible to anticipate all the possible situations beforehand. In these cases, operators need to assess the new situation or the new information on its relevance for the presently active task goal, and decide on further actions. When the situation is unfamiliar, the operator has to work out a strategy to deal with the new situation. This type of problem solving is mentally demanding, and often requires much background knowledge and expertise.

Search for information

Information is needed to maintain situation awareness, that is, a mental overview of the task situation, to be able to assess the situation, decide on appropriate actions, and assess the effects of previous actions. However, not all information may be available, or information may be ambiguous. Operators may have to make inferences about the state of the system and the environment. When information is not directly available, active search for information is needed. An important aspect of expert behaviour is knowing where and when to find information. This search for information is directed by the knowledge operators have of the present situation, the knowledge they have of similar situations (experience), and most importantly by the current task goal (Bainbridge, 1997; Neisser, 1976).

Crucial in task performance is performing the right actions at the right moment. Operators in complex tasks therefore need considerable competence, that is, “knowledge, abilities and cognition to generate appropriate behaviour given conditions in the task environment” (Smith & Hancock, 1995). Equally important for skillful performance is having a correct, updated mental overview of the momentary task situation; this is sometimes called situation awareness (although situation awareness has various definitions). The next two sections will therefore discuss situation awareness and task competence, and outline how they are acquired.

3.2 Psychological factors in task performance

Situation awareness is considered crucial in decision making in complex dynamic tasks (Endsley, 1995). Situation awareness does not merely involve knowledge of the present situation. It is defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future in light of the operator's pertinent goals" (Endsley, 1995). Correct comprehension of data and valid predictions of future states require considerable task competence; some authors equate situation awareness with the competence to know the cues and demands in the task environment that enable actions which are appropriate to the present task goal (Smith & Hancock, 1995).

3.2.1 Situation awareness

Situation awareness thus involves the perception, selection and comprehension of information, the selection of actions, and the projection of that information into the future. Adams, Tenney & Pew (1995) use the perceptual cycle of Neisser (1976) to explain how operators attain situation awareness. The main idea is that task performance, and cognition in general, does not proceed in isolation from the environment. Neisser (1976) proposed the "perceptual cycle" to describe this interdependence of perception, knowledge, and action. A person may take some action to achieve a certain goal, which brings about changes in the environment. Perception of these changes informs the operator about the effectiveness of the actions performed. This information modifies the operator's knowledge, and thus forms the basis of learning. This knowledge (represented as schemata) directs the next actions to be taken and the sampling of information. In this way, information in the environment congruent with the present schema will be perceived more quickly and more accurately because the person anticipates on that information. There is indeed empirical evidence that the search for and the selection of information present in the environment is dependent of the presently active goal (Vicente & Wang, 1998; Gollwitzer & Moskowitz, 1996).

Neisser included both an inner and an outer circle in his perceptual cycle. The inner circle includes knowledge that is currently active, information that is immediately available in the environment, and the actions presently taken. The outer circle includes the knowledge of the person that the person does have but that is presently not active, information that is not readily observable, and the actions to obtain information that is not present.

Adams, Tenney & Pew (1995) proposed to divide the immediately active schemata into two parts: explicit and implicit focus. Adams, Tenney & Pew related explicit focus to working memory, which contains a *limited* number of interrelated tokens of (or pointers to) knowledge structures in long-term memory. They assumed that the contents of explicit focus are regulated like a "push-down stack". Maintenance of this information depends on how recently it has been activated, and on its relevance for the current goal and current circumstances: the information that has been most recently activated and that is most relevant for the present goal is held on top of the stack. Implicit focus is the "full-blown representation of the underlying schema" that is only partially active in the explicit focus; it is can be equated with knowledge in long-term memory that is associated with the contents of working memory (or implicit focus). Because this information is already partially active, it is accessible more quickly than other information in long-term memory.

Schemata thus play a central role in obtaining situation awareness. Schemata can be seen as abstracted representations of complex situations, which apply over a range of comparable situations, and capture the *functional* significance of elements in the environment. They link elements in the environment (data) into coherent patterns (information). Endsley (1995) suggests that schemata are prototypical examples of situations, against which the current situation is compared. When the task situation matches a schema, actions can be selected which are appropriate in the given circumstances. Schemata thus direct information search and the actions taken. In this way, they form the declarative basis for task competence. The procedural basis for task competence is discussed in the next section, which will also discuss how task competence is acquired.

3.2.2 Task competence

As experience in complex tasks grows, perceptual cues will trigger the appropriate actions faster. At the cognitive level there are two main reasons for this: declarative and procedural learning. *Declarative learning* involves the formation and refinement of declarative structures, which at the psychological level may represent the schemata. More declarative structures will develop, covering a wider range of environmental configurations. Furthermore, these structures will become more differentiated and increasingly more in tune with the environment. The presence of these declarative structures diminishes the need for effortful problem solving in classifying and understanding the state of the environment. *Procedural learning* involves the formation of new production rules and adaptation of existing ones. These rules relate the present goal and the state of the environment to actions. As the declarative structures become more differentiated, the production rules will also become more adapted to the demands of the environment. As a result, the appropriate production is matched faster to the prevailing circumstances and the current goal, and actions will therefore become selected faster. How this goes about is discussed next.

3.2.3 ACT-R

Within the cognitive architecture ACT-R (Anderson, 1993; Anderson & Lebière, 1998), a distinction is made between declarative knowledge, consisting of chunks, and procedural knowledge, consisting of production rules. Declarative knowledge is factual knowledge that people can report or describe (“what is the capital of England?”), while procedural knowledge only becomes manifest in performance and cannot be reported directly (“how do you walk up the stairs?”). Although it is sometimes convenient to use the term working memory as consisting of the chunks that have the highest activation, a separate structure representing working memory is not part of the ACT-R architecture.

Retrieval time of chunks depends on their activation so that highly active chunks are retrieved faster. Chunks gain activation with use, and lose it over time. The level of activation of a chunk is thus partly dependent on how long ago a chunk was used previously. A major source of activation is perception: perceived objects receive immediate activation. Chunks in the focus of attention, not necessarily perceptual objects, receive activation as well. Chunks are associated with other chunks and they receive activation from these associated chunks. Goals are also declarative structures, and therefore, chunks associated with the present goal will also gain activation. In the present simulation model of ACT-R, it is assumed that, in contrast to other chunks, the activation of goals does not decrease as a function of time as long as they are on the goal stack, but this assumption has recently been challenged (e.g., Altmann & Trafton, 1999a, 1999b); this will be discussed more thoroughly in the next chapter on goals in Section 4.1.

Production rules form the basis of action, and have a condition (IF) and an action (THEN) part. The IF past describes the circumstances under which the rule will apply. The THEN part specifies the actions to be taken in those circumstances. The conditions can have different levels of abstraction, but always specify certain goal conditions that must be met for the rule to apply. Because production rules are goal-dependent, the same stimuli can activate different responses, depending on the present goal. More than one production rule may match to the state of the environment. A production rule is then selected on the basis of its expected gain. Expected gain of a production depends, among other things, on expected success in achieving the goal using this production rule (which partly depends on previous success), and the expected costs in terms of effort and time of using this production rule. This implies a preference for production rules which were previously successful and which have low effort and time costs.

3.3 Skill acquisition

The basis for a skill are production rules (Anderson, 1993). They allow the fast and stable task performance that is characteristic of expert task behaviour. Procedural knowledge develops as a result of solving problems in dealing with the environment. Usually, a novice to a task will receive some sort of instructions about how to perform the task. A new driver will, for example, receive instructions about how to change gear from a driving instructor. These instructions specify the sequence of the actions to be performed. The new driver will turn these instructions into *declarative rules*, which specify (the order of) the actions in a declarative way; for example, first release the accelerator, then press the clutch pedal, then move the gear stick, etcetera. To change gear, a production rule first has to find and retrieve the appropriate instructions. The result of this production rule is a declarative rule, for example to release the accelerator first. A second production rule is needed to interpret the declarative rule and execute the action. Retrieval and interpretation of declarative rules requires attention and working memory capacity.

The use of the initial declarative rules will produce failures and successes in achieving the goal. Examples of solutions, so-called *instances*, are stored in declarative memory. When a new task situation is encountered, these may be retrieved directly by a production rule from declarative memory and the action part of the production rule can be applied directly. Therefore, using instances in action selection involves low effort and time costs. Because instances may be matched only partially to the condition part of a production rule, the instance can also be used in situations which are not identical but only similar to the original situation. Application of the instance in a similar situation will again provide feedback about its success, and this will increase the number of useful examples in task performance. Instances may be generalised and hence cover more situations, which also improves the efficiency in task performance.

Another important mechanism in skill acquisition is the compilation of declarative rules into production rules (Taatgen, 1999). The two production rules that were initially needed to retrieve the declarative rule and execute the found instructions are combined into one production rule. The new production rule no longer needs to retrieve the instructions but directly maps the conditions to the actions. This proceduralisation of declarative rules considerably reduces the amount of attention and working memory capacity needed because the declarative rule does not have to be kept active. Although a production rule does not provide new knowledge compared to a declarative rule, use of production rules is much faster than use of declarative rules. There is no time needed for retrieval and interpretation of instructions. Also, use of production rules results in less errors in performance because no retrieval errors can occur.

As learning continues, production rules will become more and more specialised based on feedback received about the effectiveness of the associated actions. More subtle relations between elements in the environment will be recognised and followed by more appropriate responses. Declarative and procedural knowledge develop in interaction with each other, and with the task environment. For declarative structures to be successful, they should fit the functional dependencies in the environment. Whether declarative knowledge is correct is revealed by the outcome of the actions taken based on declarative knowledge. The success of procedural knowledge depends on the correct interpretation of environmental cues and production rules will usually give better performance if the selected declarative structure is the correct one. Thus, task behaviour will become increasingly more in tune with the demands and constraints of the task environment. Because building of expertise explicitly proceeds in interaction with the task environment, task performance will become optimally adapted to the specifics of the task environment. Expertise is thus highly specific, both to the task, and to the task environment in which it developed.

An important feature of production rules is that they are goal-dependent: a production rule will only fire when it matches to the appropriate goal. Although production rules become more readily selected as a function of practice, production rules will only fire when the appropriate goal is active. For example, a red traffic light will only automatically activate the actions of braking when the goal of driving is active; when one is walking, the braking response by the foot will not take place when one meets a red traffic light (Bargh, 1992). There is evidence that even implicit learning (i.e., learning without being aware of what is learned) is goal-dependent (Wright & Whittlesea, 1998).

3.4 Automatic task behaviour

At a psychological level, it thus appears that as experience grows within a given task domain, responses will be selected faster and with less effort. Task performance is said to have become automatic (Shiffrin & Schneider, 1977). It is claimed that automatic behaviour is initiated without the conscious intention to do so, performed without awareness of the actions and of the stimuli that elicited the actions, and performed without paying attention to the task. Automatic task performance is also assumed to be highly stable and not variable. The automotive theory of Bargh (Bargh, 1997; Bargh & Barndollar, 1996; Bargh & Gollwitzer, 1994) takes this position a little further. Not only the responses are triggered automatically by cues from the environment. It is argued that also the goals themselves become automatically activated by these cues when these stimuli have been consistently paired to that goal Bargh (1997) argues that goals and behavioural responses correspond to mental representations, and that therefore the same principles of automatisation should apply to them as apply to other mental representations. If a person persistently has the same goal within a specific situation, then the goal representation will become active automatically when situational features present in the environment activate the internal representation of the situation (Bargh & Gollwitzer, 1994).

The automotive theory further assumes that when the goal is activated, its associated strategies or plans to attain the goal are also activated. Furthermore, cues from the environment may also become associated with the goal-directed actions that were repeatedly successful in satisfying that goal in the past. Thus, cues from the environment trigger the goal and its associated actions automatically, without intention to perform the actions, or awareness of the triggering stimuli. As a point of interest, Bargh also assumes that not only "chronic" goals can activate the actions, but temporary goals can also trigger associated actions automatically, that is, without the deliberate intention to do so: control of actions is said to be delegated to the environment. (Bargh & Gollwitzer, 1994).

It is however highly probable that even routine behaviour is not so automatic that it proceeds without intention to perform the actions, or without awareness or attention. For example, careful observation shows that even gear changing, which is supposed to be a key example of such a routine action sequence, is highly variable (Groeger & Clegg, 1997). Changing up is more variable than changing down, and time to complete various subroutines in changing gear are affected by performing a secondary task. This indicates that performing the same sequence of actions millions of times is not in itself sufficient to produce "automatic", low-variability performance, and that performance of routine actions remains under cognitive control.

3.5 Environmental control

As expertise grows, environmental cues increasingly govern task behaviour and at a phenomenological level, it appears that action control becomes delegated to the environment (Bargh & Gollwitzer, 1994). For example, making a turn in driving needs controlled decisions at first about when to start turning the steering wheel, how far to turn it, when to let it go. Eventually, the decision to turn the wheel is taken automatically. It then appears as if curves in the road automatically direct the steering actions of the driver. Within the ecological approach of psychology, this is called an "affordance" of the road (e.g., see Suchman, 1993), by which is meant that properties of objects are simply "picked up" from the environment: they are perceived directly and do not need further processing. Although the ecological approach assumes that direct understanding of properties is innate, it is more likely the result of extensive practice and experience within a certain task domain.

With sufficient experience in a given domain, the relevant information is thus represented at a highly abstract functional level, so that one does not need to know about the details. Moreover, because production rules are not available for introspection, the details of the actions cannot be known directly, although they can be inferred or deduced from declarative knowledge.

Bargh & Barndollar (1996) and Vera & Simon (1993) noted that behaviour that runs of autonomously is not a static behavioural response, but an automated "strategy" for dealing with the environment to reach the intended goal, that is, a *general plan* concerning future behaviour. Before a task is performed (for example, driving home, or climbing through a difficult passage in mountaineering), a general strategy or plan may set out (route to climb, use of which limbs at the different locations) but actual circumstances determine the actual actions performed (when a route turns out to be to difficult, the route has to be adjusted). Not the specific actions or fixed sequences of actions are activated by cues from the environment, but strategies, which determine each successive action as a function of current information about the situation. Thus, the mental system interacts with the environment: both the general strategies and information in the environment guides actual behaviour.

In summary then, for experienced drivers, driving runs off rather autonomously under abstract goals such as “driving home”. Many actions of drivers are guided by circumstances and events occurring in the road environment, and it may appear as if control of action is in fact transferred to the environment.